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Fast-Neutron Flux in the Atmosphere

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Abstract. A fast-neutron detector was carried by balloon up to 27.4 km on November 8, 1962, from Sioux Falls, South Dakota. The detector consisted of an inner liquid scintillator, employing pulse-shape discrimination, and a thin 4π phosphor shield for rejection of charged particles. Both scintillators were viewed by a single photomultiplier. The counting rates produced by neutrons in two energy intervals between 1 and 10 Mev were recorded. The best fit to a power law spectrum was $N(E)\ dE = 2.6 E^{-1.16 \pm 0.2} \exp(-0.0069x)\ dE$ neutrons/cm² sec Mev in the equilibrium region. The counting rate rose to a broad maximum at about 75 g/cm², where the total flux of neutrons between 1 and 10 Mev was 1.9 neutrons/cm² sec. The flux at floating altitude was 1.4 neutrons/cm² sec. The results are compared with those of Newkirk and of Hess.

Introduction. The collisions of high-energy cosmic-ray primaries with air nuclei initiate a chain of events in which neutrons are produced, along with other secondary particles. The spatial and energy distribution of these neutrons depends on (1) the rate of production of neutrons in nuclear disintegrations and the energies with which they are emitted, (2) the processes by which they are slowed down and captured, and (3) the rate at which they escape from the top of the atmosphere. The total processes resulting in neutron production will be called the neutron source. If the spectrum of the neutron source is known at any atmospheric depth, the steady-state flux and energy distribution can be determined. This involves applying the cross sections for elastic and inelastic collision with nitrogen and oxygen to the solution of the Boltzmann transport equation. *Hess et al.* [1961] made such a calculation. They chose a distribution and spectrum of source neutrons consistent with measurements made by *Hess et al.* [1959] of the flux at various energies and at altitudes up to 12 km. A neutron diffusion code developed for the IBM 704 was used to extend these results to the top of the atmosphere. *Newkirk* [1963] calculated the neutron flux through the atmosphere by the S_n method, a numerical approximation to the solution of the transport equation. He assumed a neutron source derived from the observations of others. The resultant flux was normalized to that measured in two energy regions by *Smith et al.* [1961, also *Reagan and Smith*, 1963].

The neutron energy spectrums published by Hess and by Newkirk agree within the uncertainties discussed by Newkirk except in the energy interval from 0.1 to about 5 Mev. In the past, measurements of neutrons in this region were generally made using slow-neutron counters surrounded with moderating material. With such a detector, local production of neutrons in the moderator by high-energy particles adds a significant and not readily calculable contribution to the measured counting rate of fast neutrons.

The purpose of the experiment described in the present paper was twofold. First, it was desired to obtain more information about the neutron flux between 1 and 10 Mev from sea level to balloon altitudes. Second, it was desired to develop and test a fast-neutron detector that had optimum efficiency for neutrons and was insensitive to other radiation.

Experimental method. Figure 1 is a cross section of the fast-neutron detector (fabricated by Nuclear Enterprises, Ltd., Winnipeg, Canada) used in this experiment. It was a liquid scintillator NE 213, 5 cm in diameter and 5 cm deep, encapsulated in 6 mm of plastic phosphor NE 102. The combination was viewed by a single photomultiplier. Neutrons were detected by identifying the recoil protons they produced in the inner scintillator. Charged particles and γ
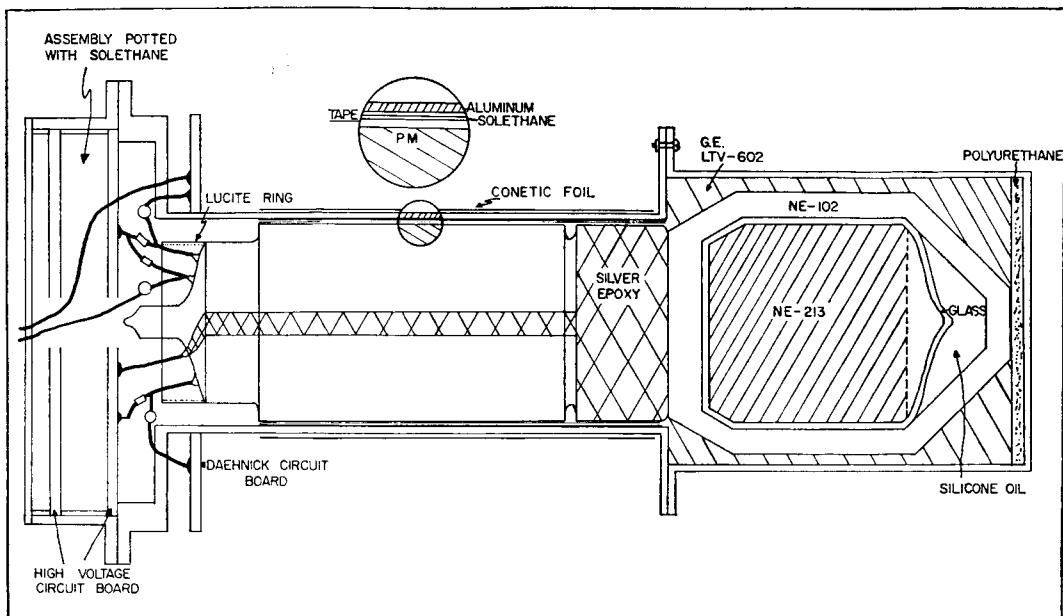
Fig. 1.   Cross section of scintillator and photomultiplier tube assembly.

rays were rejected by pulse-shape discrimination techniques.

The principles employed in the inner scintillator are briefly as follows. Light impulses from an oxygen-free phosphor exhibit two main modes of decay, one less than 10 msec in duration, the other more than 100 msec. For the same peak-pulse amplitude, the amount of light output after 10 msec is greater the more heavily ionizing the particle producing the excitation [Owen, 1958]. This variation in pulse shape can be detected by standard electronic techniques. Thus, electrons have been separated from protons in the same light output interval by the greater peak-to-valley ratio of the electron pulses [Brooks, 1959; Daehnick and Sherr, 1961].

The inner liquid scintillator of the flight detector separated neutrons from γ rays by distinguishing between the protons and electrons they produced. In the outer plastic phosphor, the pulses from both heavily and lightly ionizing particles exhibited a shape nearly the same as that from electrons, so that charged particles stopping in the outer detector were also rejected by pulse shape. The dimensions of the plastic shell were such that charged particles penetrating the inner detector were rejected either as lightly ionizing particles, causing an output similar to that of an electron, or as particles producing a greater light output in the detector than in the upper discrimination level of the circuitry. Further details of the detector can be found elsewhere [Mendell, 1963].

In the flight apparatus, transistorized circuits amplified and sorted counts produced by two energy ranges of recoil protons, as well as all ionizing events with a light output above a 1-Mev proton bias. The counting rate information was applied in the form of 1-msec signals to a FM/FM telemetry system operating at a carrier frequency of 1680 Mc/s. A block diagram of the flight instrumentation is shown in Figure 2. The two channels of neutron information, which we shall call logic I and logic II, counted recoil protons between 1 and 3.3 Mev and between 3.3 and 6 Mev. The bias levels were determined from the Compton edge of Co^{60} and of Cs^{137} γ rays in the inner detector. Gain stability was checked with the γ-ray sources and with a Pb^{210}-Be neutron source before and after the flight. Since the proton-recoil spectrum from a neutron collision extends from zero to the neutron energy, the detector had an appreciable sensitivity for 10-Mev neutrons (Figure 3). To convert the counting rates of
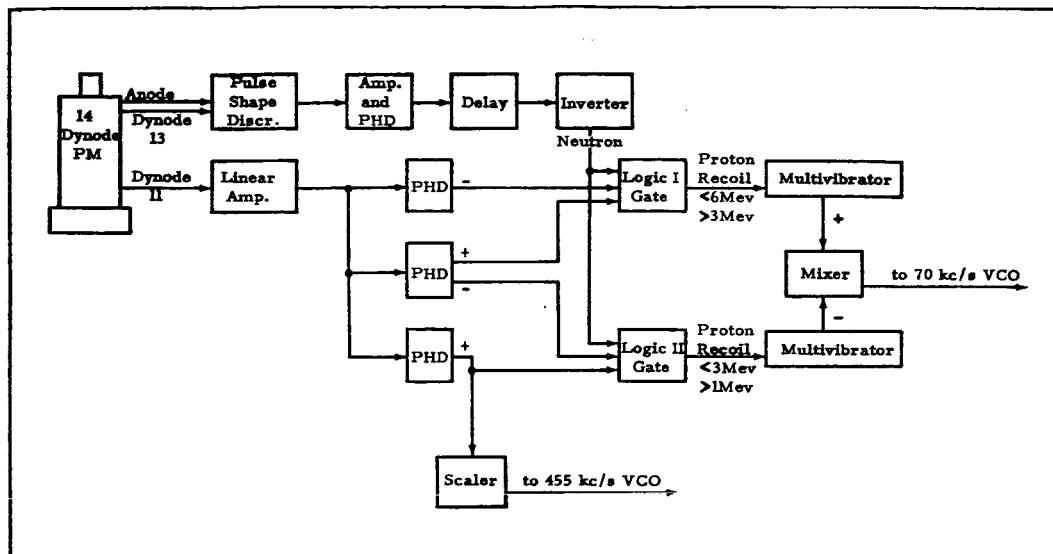
Fig. 2. Block diagram of amplifying, pulse-shape discriminating, and logic circuitry.

logic I and logic II into flux, the composite detector was calibrated against a Pu-Be source of known strength (Mound Laboratory, Monsanto Research Corporation, Miamisburg, Ohio). The over-all efficiency of the detector to neutrons between 1 and 10 Mev from the Pu-Be source was measured, as well as the ratio of counting rates of the two neutron channels. The relative efficiency to neutrons of different energies was obtained by comparing the proton-recoil spectrum of the composite detector, as measured with an RIDL multichannel analyzer, with a theoretical spectrum calculated from the following information: (1) the Pu-Be neutron differ-
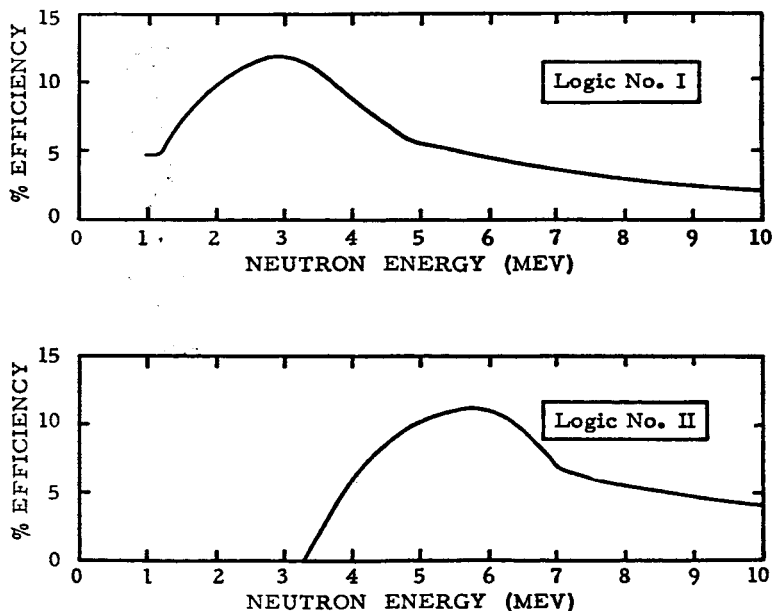

Fig. 3. Efficiency of logic I and logic II for neutrons between 1 and 10 Mev. Estimated uncertainty of efficiency is about 10 per cent.

ential energy distribution measured by *Broek and Anderson* [1960] and (2) the collision probability and the recoil-proton light output spectrum for neutrons of various energies at normal incidence to the axis of a cylindrical container of NE 213, 5 cm in diameter and 6.3 cm long [*Batchelor et al.*, 1962]. The measured spectrum was matched to the calculated spectrum at proton-recoil energies above 3 Mev. Between 1 and 3 Mev, the shape of the calculated and the measured spectrums differed because the neutron-gating pulse, which had a deliberately high threshold (to optimize rejection of charged particles in NE 102), did not always accompany a proton recoil. The ratio of the height of the experimental to the theoretical spectrum in the 1- to 3-Mev region gave the fraction of proton recoils in each light output interval actually counted by the flight circuits. The efficiency of the composite detector versus neutron energy thus calculated is shown in Figure 3. These values, numerically integrated over the Broek and Anderson spectrum, with limits of integration defined by the discriminator levels, reproduced the measured over-all efficiency and ratio of counting rates in the two neutron channels. The uncertainty in the values of Figure 3 was estimated to be about 10 per cent.

The calibration procedure up to this point was for a beam incident normal to the axis. The average over-all efficiency for an arbitrary angle of incidence was measured and found to be 0.82 of that observed for the beam normal to the axis.

The flight detector and its transistorized high-voltage supply were tested and flown in a pressure-sealed container. The gondola was specially designed to have minimum mass in the vicinity of the detector and to have optimum thermal isolation from the environment.

Experimental results. New York University flight 104 was launched November 8, 1962, from Sioux Falls, South Dakota, geomagnetic latitude 53°N, at 0828 CST. It was a geomagnetically quiet day; it was also a quiet day for man-made radiation. A 3500-m³ balloon, supplied by Raven Industries, carried the instruments to altitude and floated at about 27.4 km. Transmission of data from the neutron channels was good until 170 minutes after launch. The counting rate at altitude remained constant for 50 minutes, after which the counting rate in the

total ionizing events and lower energy channel began to increase slowly until the signal faded. Figures 4 and 5 are plots of counting rate versus altitude. It is observed that both logic channels showed, within statistical error, the same rate of increase of counting rate with decreasing pressure. The mean attenuation length of the total neutron counting rate in the interval between 200 and 600 g/cm² of atmospheric depth was 145 ± 6 g/cm², according to a least-squares calculation. The counting rate rose, on ascent, to a broad maximum around 75 mb, after which it decreased by about 25 to 30 per cent at the top altitude reached.

To convert counting rate to neutron flux, some knowledge of the spectrum is necessary, since the detector efficiency is energy dependent. From the results of Hess and of Newkirk, and from cloud chamber measurements of cosmic-ray neutrons at mountain altitude [*Miyake et al.*, 1957], the neutron flux between 1 and 10 Mev can be expected to decrease monotonically with energy. We approximate the differential energy spectrum between 1 and 10 Mev by a power law of the form

$$N(E) \ dE$$
$$= N(1)E^{-n} \ dE \quad \text{neutrons/cm}^2 \text{ sec Mev} \quad (1)$$

where $N(E) \ dE$ is the flux of neutrons of energy E to $E + dE$, n is a constant, and $N(1)$ is the flux of neutrons/Mev at 1 Mev. The integrated efficiency varies by less than 3 per cent of its value for n between 0 and 2. The ratio of the counting rate of logic I to that of logic II is, however, quite sensitive to n. The value of n which gave the closest fit to the ratio logic I/logic II, between 200 and 700 mb, was 1.16 ± 0.2. Each point was given equal statistical weight; the deviation represents the flight statistics only and does not include uncertainties in calibration. For this spectrum, the response of the detector to an incident flux of 1 neutron/cm² sec was 2.17 counts/sec. At floating altitude, the value of n, averaged over the first 50 minutes, was 1.10 ± 0.2. Using the detector response determined above, the neutron flux is plotted against pressure in Figure 6. The observed total flux of neutrons between 1 and 10 Mev at the maximum counting rate was 1.9 neutrons/cm² sec. The flux at the floating altitude of 27.4 km was 1.4 neutrons/cm² sec.
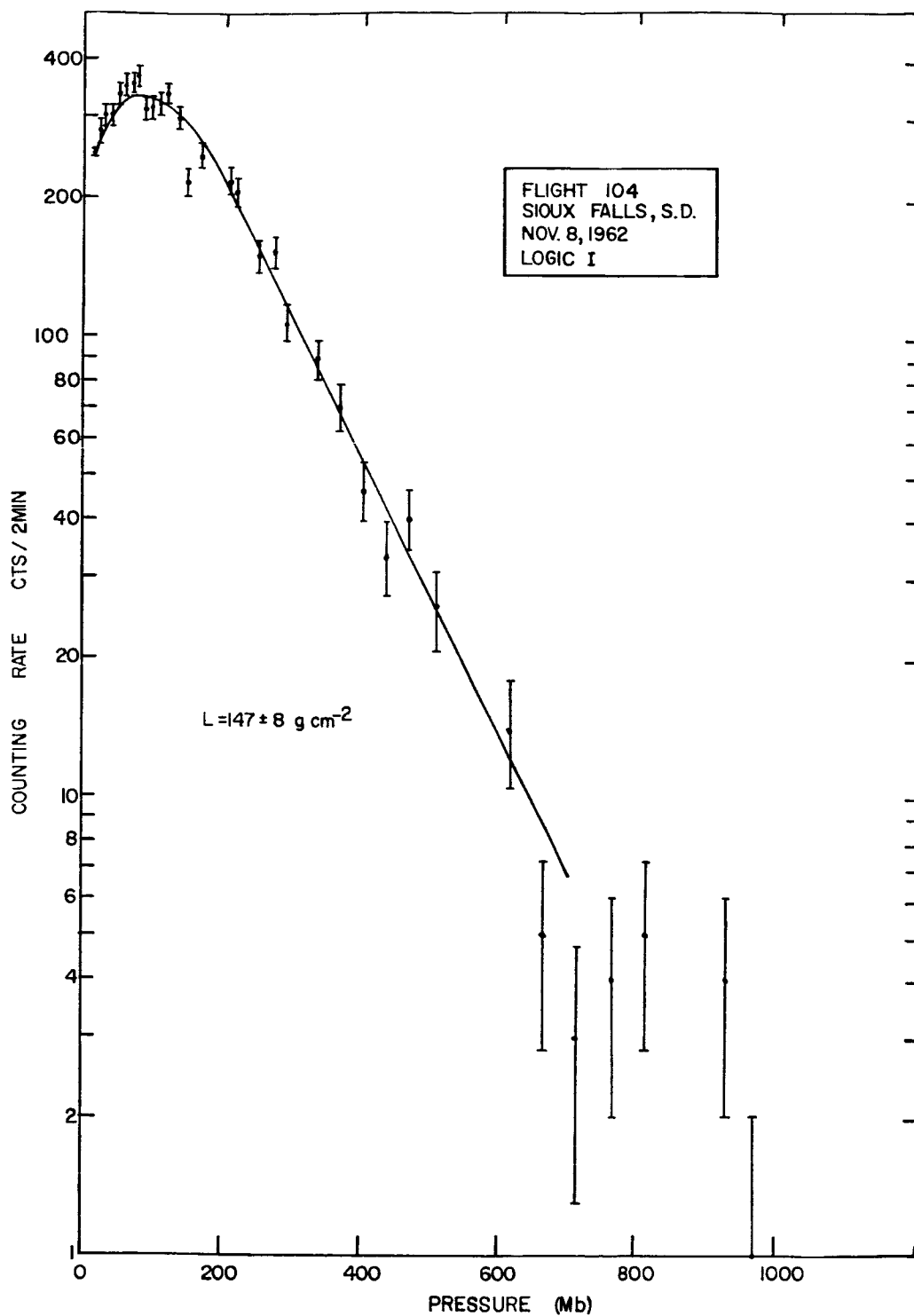
Fig. 4. Neutron counting rate versus atmospheric pressure, proton-recoil energy 1 to 3.3 Mev.

FLIGHT 104
SIOUX FALLS, S.D.
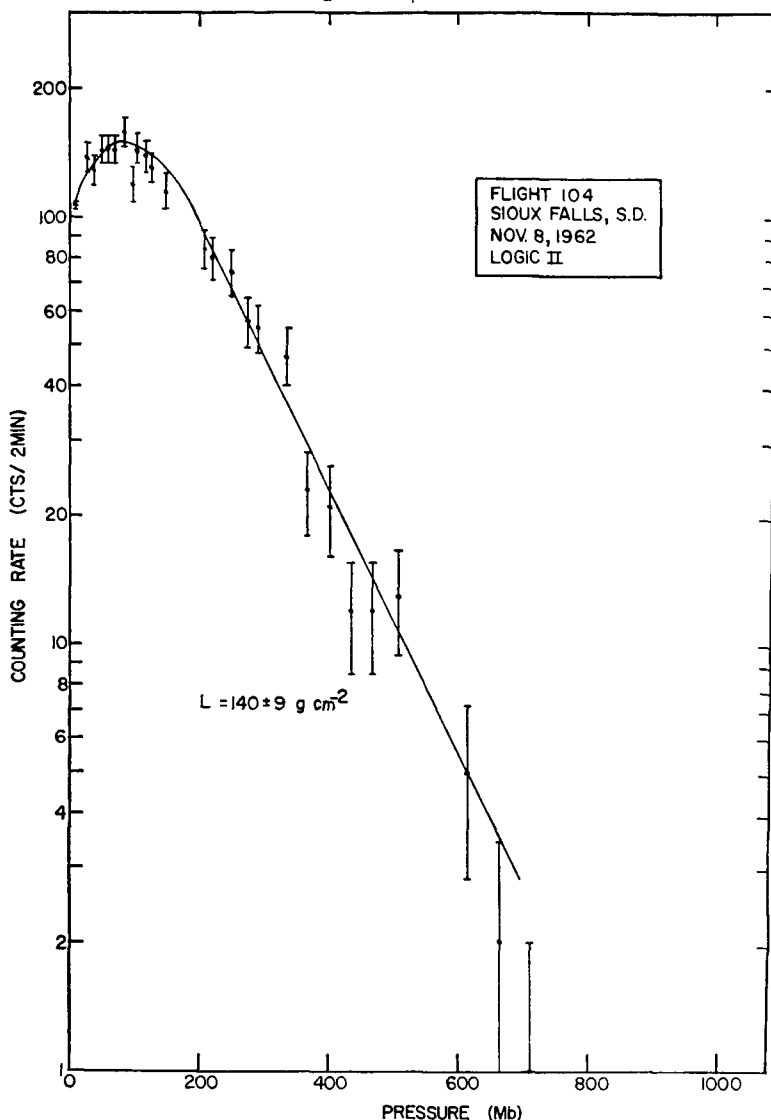NOV. 8, 1962
LOGIC II

$L = 140 \pm 9$ g cm^{-2}

Fig. 5.   Neutron counting rate versus atmospheric pressure, proton-recoil energy 3.3 to 6 Mev.

The differential flux at atmospheric depths between 200 and 600 g/cm^2 can be expressed as

$$N(E) \, dE = 2.6E^{-1.16 \pm 0.2}$$

$$\cdot \exp - (0.0069x) \, dE \text{ neutrons/cm}^2 \text{ sec Mev}$$

where x is atmospheric depth in g/cm^2.

Discussion.   To compare our observed fluxes with the results of Newkirk and Hess, we made a normalization correction for the variation of the neutron flux at different altitudes with lati-

tude and with time of the solar cycle. The experiments and calculations were based on results at different latitudes and times. In Figure 7 we have plotted directly points taken from the curves of Newkirk and Hess. The dashed curves associated with the points have been normalized to $\lambda_s = 53°N$ and to a time intermediate between solar minimum and solar maximum (i.e., November 1962). The solid line is the power law approximation to the spectrum of flight 104. The variation of the flux
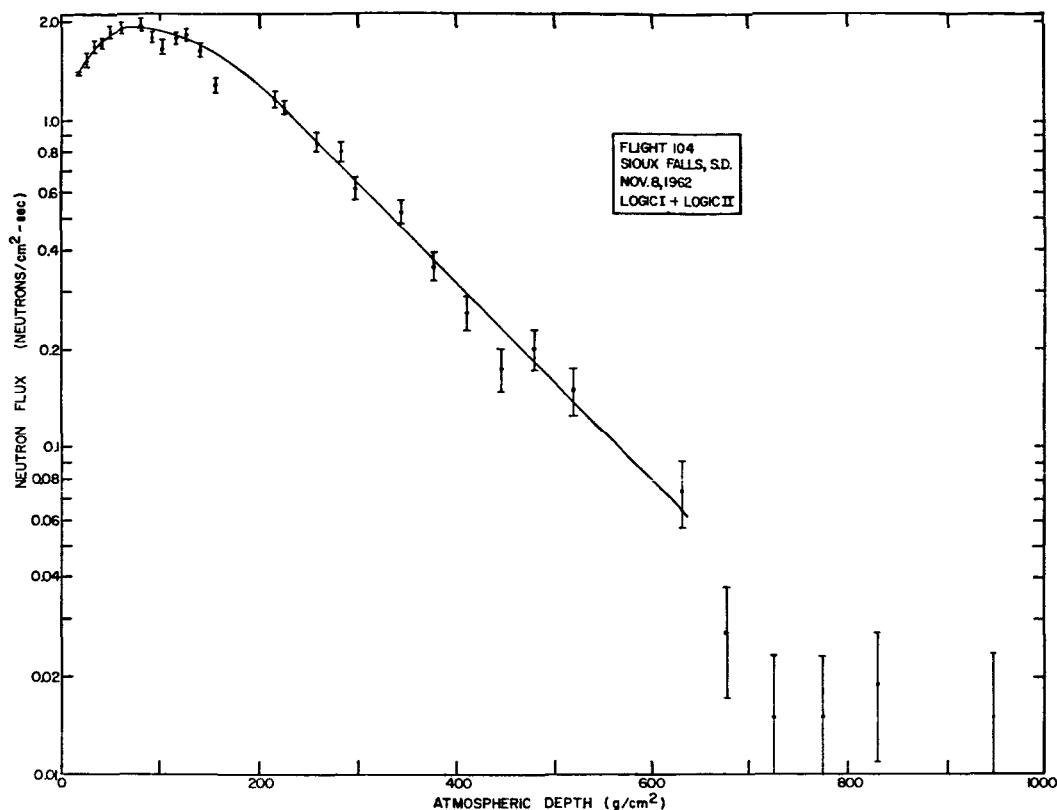
Fig. 6. Neutron flux between 1 and 10 Mev versus atmospheric depth.

of nucleonic component at different altitudes with time and latitude was estimated from the work of various authors including *Whyte* [1951], *Simpson et al.* [1951], *Meyer and Simpson* [1955], *Simpson and Fagot* [1953], *Soberman* [1956], and *Pomerantz et al.* [1960].

Our measurement of the spatial and energy distribution of the fast-neutron flux is consistently 30 per cent higher than that calculated by Newkirk. This can be considered to be in good agreement, within the uncertainties of Newkirk's calculation, of our measurement and of the time variation of the neutron flux. The neutron production rate in the atmosphere reported by Newkirk is consistent with the results of our experiment.

The fluxes measured by Hess appear to differ from the results of flight 104 mainly at the low-energy end of the spectrum, in the equilibrium region. The over-all flux from flight 104 was 50 to 60 per cent of the normalized flux reported by Hess at atmospheric depths between 200 and

700 g/cm^2. At 40 g/cm^2, where Hess used a diffusion calculation, his value, normalized to 53°N, is larger than the flux of flight 104 by a factor of 3. This may be compared with the factor of $\frac{1}{3}$ by which the calculations of Hess were multiplied by *Bame et al.* [1963] to conform with measurements made at altitudes of 320 to 650 km, although their results were consistent with the shape of the spectrum calculated by Hess. The differential energy spectrum in the region from 1 to 10 Mev appears to require further investigation. A measurement of *Miyake et al.* [1957] found the differential distribution to vary, at 760 g/cm^2 as $E^{-1.25 \pm 0.1}$ between 1 and 15 Mev. A measurement at sea level by *Kastner et al.* [1963] yielded results consistent with the steeper spectrum of Hess. The energy interval is of interest because it is believed to contain a large percentage of the source neutrons [*Hess et al.*, 1961] because of its relation to neutron albedo theory of the Van Allen belts and because of the importance of the fast-neutron con-
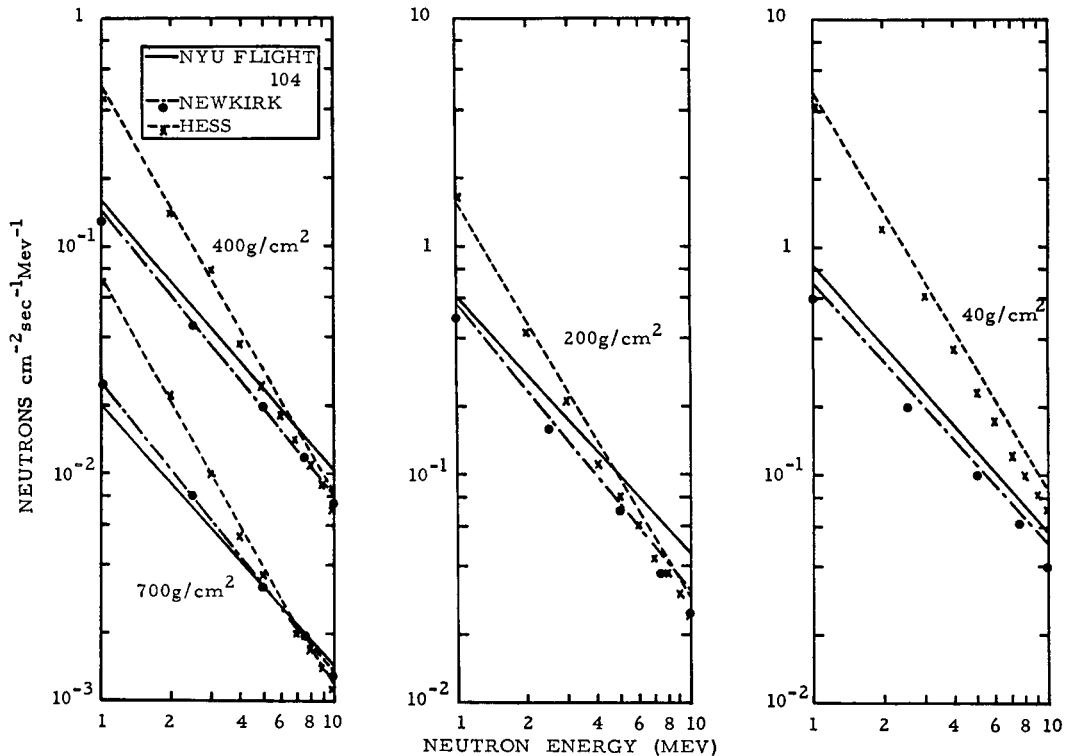
Fig. 7. Differential neutron energy spectrum from 1 to 10 Mev. Circles and crosses are taken directly from the curves of Newkirk and of Hess et al. Dashed lines represent the spectrums of Newkirk and of Hess, normalized to $\lambda_g = 53°N$, November 1962. Solid lines are power law approximation to neutron spectrum derived from results of flight 104. Above 700-g/cm^2 atmospheric height, the estimated uncertainty in flux is within the 25 per cent estimated uncertainty of the measurement by Hess and of the calculation of Newkirk.

tribution to the radiation dose in the upper atmosphere. Further flights are planned, in which this problem will be investigated among others.

A quantity which should be independent of neutron production in the moderating material around a slow-neutron detector is the mean attenuation length L. In the equilibrium region of the atmosphere the fast and slow neutrons do not diffuse far from their point of origin. The neutron-producing radiation attenuates more slowly, partly because an inelastic collision can be accompanied by further production of high-energy particles. The flux or density of both the fast and slow neutrons as a function of elevation is described by the longest attenuation length, that of the neutron-producing radiation in the 'equilibrium region.'

The value of 145 ± 6 g/cm^2 found in this experiment at $\lambda_g = 53°N$ and the value obtained

by Hess of 155 g/cm^2 at $\lambda_g = 44°N$ during a similar period of cosmic-ray activity is consistent with the sign of the latitude effect observed by *Soberman* [1956] and by *Meyer and Simpson* [1955]. The value of 142 g/cm^2 obtained for slow neutrons by *Haymes and Korff* [1960] during solar maximum at $\lambda_g = 55°N$ is consistent with the altitude independence of the neutron energy distribution in the equilibrium region of the atmosphere.

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